

A METHOD FOR THE
QUALITATIVE ANALYSIS
OF MUSICAL TONE

DISSERTATION

SUBMITTED TO THE BOARD OF UNIVERSITY STUDIES
OF THE JOHNS HOPKINS UNIVERSITY
IN CONFORMITY WITH THE REQUIREMENTS FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY

BY
PRESTON HAMPTON EDWARDS

BALTIMORE
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I. INTRODUCTORY.

THE present investigation was undertaken with the purpose of making an analysis of the musical tones actually emitted from a violin or other musical instrument. The problem of the quality of tones has engaged the attention of many investigators, yet no systematic quantitative results have been obtained. Helmholtz¹ did a great deal in the analysis of tones, both from consideration of the method of their production, as in the case of the vibration of a violin string and that of the air used in an organ pipe; and by his resonators, which gave an indication of what was actually going on in the air. Koenig² attacked the problem with resonators and manometric flames, while Scripture³ studied enlarged phonograph records. Dayton Miller⁴ has recently used an improved oscillograph method.

As has been said, none of these methods has as yet furnished quantitative results, and they can hardly be expected to do so unless greatly improved in the future. The use of resonators by Helmholtz and Koenig depends on the human ear in one case and on manometric flames in the second, and either can only give qualitative results. The other methods are dependent on the analysis of irregular curves, which is a difficult and not always certain process. There is also in many cases the complication introduced by the membrane or other parts of the recording device having free periods of their own. So the first step of this work was to look for a better method of analysis.

¹Tonempfindungen, Abs. 3, 4, 5.

²Expériences d'Acoustique, p. 70 ff.

³Elements of Experimental Phonetics.

⁴Reported at Baltimore meeting of A. A. A. S., Dec., 1908.

II. THE METHOD.

The first device tried was one used by M. Wien,¹ who cut away a portion of the wall of a Helmholtz resonator and replaced it by a metallic diaphragm tuned to the tone of the resonator. The vibrations of this diaphragm were communicated by a stylus to a light steel spring extending over the diaphragm from a support at the side, and on the end of the spring was mounted a small mirror forming an image of a slit on a screen, to indicate the amplitude of the vibrations. In my tests a cylindrical resonator was used, with the usual small orifice at one end, while at the other end was a larger opening, over which membranes of various sorts could be placed and held fast by a flat brass ring screwed on. It was soon found, however, that the system formed by the coupling of these two units, instead of having a single response, answered to two notes several tones apart, even though the two were tuned to the same frequency before coupling. This fact makes its indications doubtful, thus rendering it useless for the purposes of this investigation. Following this some tests were made with Rayleigh's disk,² which finally led to the adoption of a system composed of a mica disk hung close in front of the opening of a resonator, at an angle of 45° with the plane of the opening.

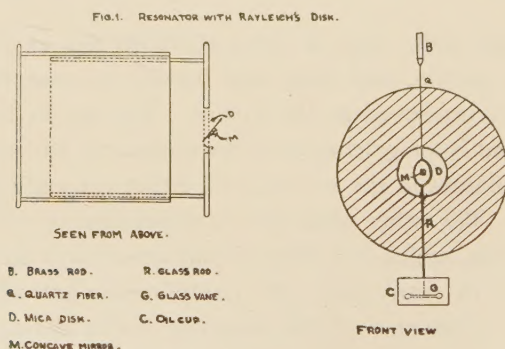


Fig. 1.

The arrangement of this system may be readily understood from the accompanying sketches (Fig. 1). The disks were made of mica,

¹Wiedemann's *Annalen*, 36, p. 835, 1889.

²Rayleigh, *Theory of Sound*, II., p. 44.

on account of its lightness and ease of handling. The circles were cut out with a pair of bow dividers with sharpened points. The concave mirrors were made by silvering, or better, platinizing the surface of a concave eyeglass lens such as can be obtained from opticians, having by reflection a focal length of about 50 cm. After silvering the lens it was cut into strips and chips struck off from the surface by hitting the edge with a hammer. Mirrors can be made in this way of 1 milligram or less in weight, which will give a good image of a Nernst filament at one meter's distance. The quartz fiber could be made of any fineness, according to sensibility desired. At the bottom of the disk was attached a fine glass rod, and at the lower end of this was a little glass dumbbell hanging in a cup of kerosene for damping. The motion of air in and out of the mouth of the resonator when it is "speaking," exerts a couple on the disk, tending to set it in the plane of the opening, and the deflection of the image thrown by the mirror on a screen measures the angle through which it turns.

The cylindrical form of resonator made of two pieces of telescoping brass tubing was chosen on account of ease of tuning. The larger ones were made by Koenig, of Paris, and were kindly put at my disposal by the psychological laboratory of this university. In use the nipples made for insertion in the ear were closed with small corks. The smaller ones were made in the workshop of this laboratory, and had no nipples (see Fig. 1).

A series of 17 resonators was set up in this manner, for the analysis of the tones g and c' . (In this paper Helmholtz's designations will be used for the notes, and the partials will be designated by their relative frequency numbers, *i. e.*, the fundamental will be called the first partial, the octave the second, etc.) The whole set up comprised the following:

Partials of g .

1. g
2. g'
3. d''
- * 4. g''
5. b''
6. d'''
- * 8. g'''
- * 12. d^{IV}

Partials of c' .

1. c'
2. c''
- * 3. g''
- * 4. c'''
5. e'''
- * 6. g'''
7. bb''' (app.)
8. c^{IV}

(a) *Multiplying Factor of the Resonator*, which has been shown by Helmholtz to be expressed by the formula $dp/dP = \sqrt{2R^3/\pi^2 S}$ (see page 29).

This gives a comparatively low value for the resonators corresponding to the higher partials, since their openings are in general larger in comparison to their volumes than for the lower resonators.

(b) *Size and Length of the Quartz Fiber*.—We can always increase the sensibility in this direction, at the expense of stability and ease of handling. A proper balance between these two desiderata must be found for any one investigation; in the present work no attempt was made to push the sensibility to extreme values.

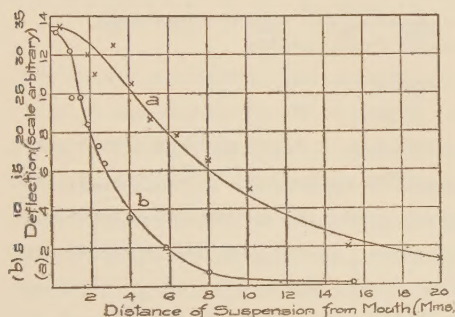


Fig. 3.

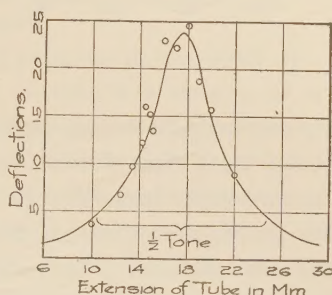


Fig. 4.

(c) *Size of the Disk*.—Lord Rayleigh's formula for the couple is: $M = \frac{4}{3}\rho a^3 W^2 \sin 2\theta$ (where a = radius of disk, W = mean velocity of vibrating particles, ρ = density of air, and θ = inclination of disk to plane of mouth), which shows that the effect can be increased by increasing the diameter of the disk, in proportion to the cube of this diameter. The size of the disk, however, must be kept well under the size of the resonator's mouth. It was thought that the presence of the disk might have the same effect as reducing the size of the mouth, *i. e.*, might lower the pitch of the resonator, but a test with several persons of good musical ear did not indicate such an effect in the slightest degree.

(d) *Distance of Suspension from Plane of the Mouth*.—In Fig. 3 are shown curves between these distances and the deflections produced by a constant source of sound (an organ pipe blown at uniform pressure). This would afford an easy way of varying the sensibility

if so desired. In this work the distance was kept constant, and as small as practicable (about 1 mm.).

2. *Selectiveness.*—Fig. 4 shows a curve of deflection obtained when the tuning was varied by drawing out or forcing together the two telescoping tubes forming the resonator, the source of sound being kept constant. The extension corresponding to a semitone change of pitch is indicated in the figure. Quite similar curves were obtained when the source of sound was tuned (*e. g.*, an organ pipe tuned by turning down a portion of the top margin, and compared

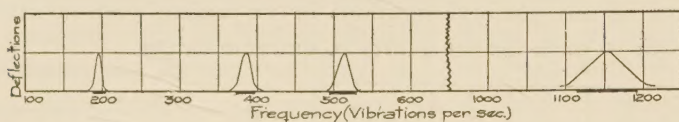


Fig. 5.

by beats with a tuning fork). In Fig. 5 four of these curves are plotted on a line of abscissas which represents total frequencies. The heavy line beneath each curve indicates a range of a semitone. This sketch shows us that neighboring harmonics will not interfere until we reach the neighborhood of the sixteenth, where they are about a semitone apart. It will be noticed that the g' and d'' resonators, which were cylindrical, were less selective than the g and c'' , which were of the Helmholtz pattern. Whether this is due to their cylindrical shape, or to some relation between volume and size of mouth, has not yet been investigated.

3. *Damping.*—It was found possible by the arrangement of a glass rod dipping in oil as shown in Fig. 1, to make the vibrations of the disk practically dead beat, so that in a fraction of a second the image on the scale, on the sounding of its tone, will move to a position which will be steady so long as the pitch and intensity are constant. Of any variation in either, however, it is a very delicate indicator, and it often warns the observer that a note sung is not holding to its pitch when his ear does not notice the fact.

4. *Indications.*—It will be noticed from the formula for Rayleigh's disk, that so long as the deflections are small, *i. e.*, θ very near 45° , the turning couple, and therefore the deflection, is proportional to the kinetic energy of vibration of the air at the resonator's mouth.

If therefore we know the "multiplying factor" of each resonator and the moment of torsion of each suspension, we can pass at once to the absolute energy belonging to each partial, in the open air. It seems more to the point to describe the quality of a tone by the energy of its components than by their amplitudes, and in the graphical representations of tone quality in this paper, the strength of each partial will be indicated by ordinates proportional to its energy of vibration, obtained immediately from the deflection of the corresponding disk, by the use of the two constants just mentioned. Helmholtz's formula for the multiplying factor of a resonator is

$$dp/dP = \sqrt{2R^3/\pi^2S},$$

where dp represents the variation of pressure in the outer air, dP that in the resonator, R = radius of mouth, S = volume of resonator. Where we have to do with energy values, however, we must use the square of this ratio. Wien¹ experimentally found values in the neighborhood of 30 per cent. below the theoretical values as given by the above formula. His method however is not one which may be considered as accurate, and it is highly desirable that some means be found of experimentally arriving at a value of this ratio. Much time and effort were expended in this direction in connection with the present work, but no results worth recording were obtained. The writer hopes to continue these experiments in the near future. Meanwhile the theoretical value will be used in this paper.

To find the reducing factor for the suspended system, a system similar to those in use with the resonators, was suspended in a vacuum and its period observed. It was then removed and a piece of copper wire about as long as the diameter of the disk, was attached, by a bit of wax, along a horizontal diameter of the disk. The period was again observed in a vacuum, and since the moment of inertia of the piece of wire could be calculated, the moment of torsion of the quartz fiber was thus found. Each suspension was then directly compared with this standard by suspending the two successively in front of the same resonator and taking deflection produced when the note of the resonator was sounded by an organ

¹M. Wien, *l. c.*

pipe at a definite air pressure. This comparison gives a factor by means of which the deflection of any suspension may be at once reduced to the equivalent deflection of the standard. Multiplying this deflection by its known moment of torsion gives M in the formula

$$M = \frac{4}{3}\rho a^3 W^2 \sin 2\theta.$$

Measuring a , the radius of the standard disk, and taking $\sin 2\theta = 1$, since θ does not vary much from 45° , the deflections being generally small, we have a means of calculating $\frac{1}{2}\rho W^2$, the mean kinetic energy per c.c. of the vibrating air at the resonator's mouth, and multiplying this by the factor $2R^3/\pi^2 S$ we find the mean kinetic energy per c.c. in the air, belonging to the corresponding partial. For the present purpose the deflections were reduced to the equivalent deflections of the standard and then multiplied by the factor $2R^3/\pi^2 S$, thus giving quantities *proportional* to the energy of the various partials.

It would be interesting to use this method to compare the total input and output of energy for various musical instruments, thus giving their efficiency as sound producers. Webster¹ has arrived at values of this efficiency, using only a single partial (the fundamental). The present work indicates that for many instruments his values would be very largely increased by taking account of all the partials.

IV. ROOM USED FOR THE TESTS.

In the preliminary trials it was found that the quality of a tone might vary greatly as the instrument producing it was moved about the room. This effect is doubtless due to standing waves produced by reflection from the walls of the room, and depends on the position of the source and of the receiver, and on the wave-lengths of the sound. The difference of wave-length of the different partials causes some to be weakened by interference at certain points, while others are strengthened, and so on. The curves in Fig. 6 show the effect on the relative strength of the first three partials of a c' reed pipe, when the pipe was moved perpendicularly away from the

¹A. G. Webster, *On the Mechanical Efficiency of the Production of Sound*, Leipzig, 1904.

wall of the room, its height from the floor being kept constant. The room was an octagonal one about 4.5 meters across. The resonators were near the opposite wall of the room. It is interesting to note that the maxima (or minima) of the first and third partials are found at points separated by distances nearly equal to their respective wave-lengths (for first partial $\lambda = 130$ cm., for third,

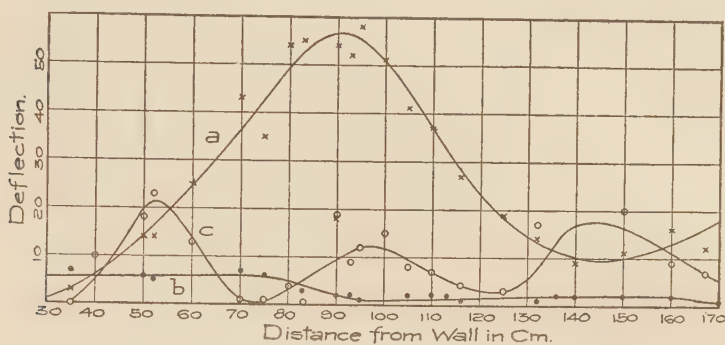


Fig. 6.

$\lambda = 43$ cm.). It would be easier to explain this if the distance were $\frac{1}{2}\lambda$. The second partial does not show any such marked effect as the other two.

In order to eliminate complications arising from this effect, a space was curtained off by burlap lined with cotton batting, forming a chamber about 10 feet by 6 feet by 7 feet, in one end of which was placed on a table the set of resonators protected by the paper covered box. The performer with his instrument stood at the other end of this chamber. The floor, as well as the sides and top, was covered with cotton batting about an inch thick. It is probable that even with all the precautions taken there were still complications present due to shadows and reflections, since the observer and the screen were between the performer and the resonators, and the table and other solid articles offered a considerable area of reflecting surface. In the more extended experiments which it is hoped will follow, a larger room must be prepared in which the observer and screen may be to one side, and solid materials reduced to a minimum. The table, for instance, might be made of slender steel rods with a top made of iron gauze. It would be advantageous to carry on

experiments in an open space out of doors, if such were available where the air would be sufficiently still.

V. TAKING THE OBSERVATIONS.

The manner of doing this was the simplest possible. The suspensions were so adjusted that each mirror threw an image of a Nernst glower on a screen, and the observer sitting in front of the screen soon became familiar with the position of the image corresponding to each partial. The performer stood behind the observer and produced a given tone half a dozen or a dozen times while

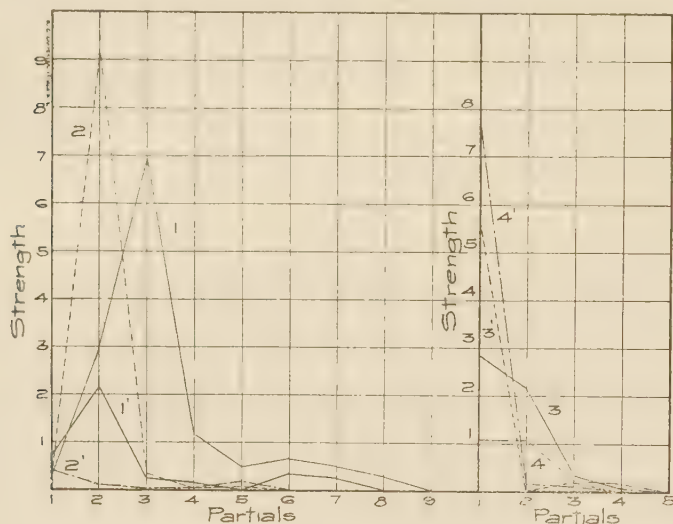


Fig. 7.

the latter noted the deflections of the images. There were often differences of as much as 100 per cent. in the deflections of the same image for successive productions of the same note, so an average value was taken. The following set of readings is given as an illustration. The column of readings headed by *m* under each tone was taken with the violin muted with a metal mute. An asterisk (*) indicates that there was no resonator to respond to that partial.

The figures must be modified as explained under III., 4, to show the actual proportions of the total energy of the tone, furnished

by the several components. This has been done to obtain the ordinates used in Fig. 7. It must be borne in mind that in this and similar graphical representations of tone quality only the ordinates have a meaning, the lines joining the summits of these ordinates being merely a means of showing that these ordinates belong to the same tone, in a way to appeal easily to the eye.

Record of P. H. E.'s Violin, played by A. H. P.

Partials.	Open g.		c'		g' Harmonic.		on d' String.		c''		g''	
		m		m		m		m		m		m
1.	.4	1.0	.7	2.0	6.5	13.0	2.5	18.0	30.0	.9	6.9	3.0
2.	3.4	2.5	24.0	.3	3.0	.0	1.5	.2	.8	.4	.3	.5
3.	9.0	.3	2.5	.2	.3	.2	.2	.1	.2	.0	.0	.0
4.	.8	.1	.2	.1	.1	.0	.2	.0	.5	.0	.0	.0
5.	.8	.0	.2	.5	*				.0	.0		
6.	.3	.2	.2	.0	.0	.0	.0	.0	.0	.0		
7.	.2	.1	.0	.0	*				*			
8.	.2	.0	.0	.0	.0	.0	.0	.0	.0	.0		
12.	.0	.0	.0	.0					*			
16.	.0	.0	.0	.0								

A more refined method of taking the observations would be, by means of auxiliary mirrors, to bring all the images into one vertical line, also to so adjust the sensibility of the systems that their deflections would all bear the same proportion to the energy of the corresponding partial in the open air. Then a film could be exposed while the tone was sounding and while not sounding, and the displacements of the images would give a picture of the instantaneous quality of the tone.

VI. DISCUSSION OF THE RESULTS.

The readings given in the table above, and (in part) represented graphically in Fig. 7, bring out at once two remarkable and important facts, (1) that the lower tones of the violin are extremely weak in fundamental, a very large proportion of the energy being contained in the overtones, and (2) that the effect of muting these tones is to increase, not only relatively but absolutely, the strength of the fundamental, while damping the upper partials. Muting the higher tones diminishes all of the partials together.

Fig. 8 shows the effect of different manners of bowing, in a somewhat exaggerated way. Record (1) is from a good English-made Amati model, about 150 years old, bowed by a good violinist to bring out its best effect; (1') is from the same violin bowed with great force by another performer, to bring out its full power. It

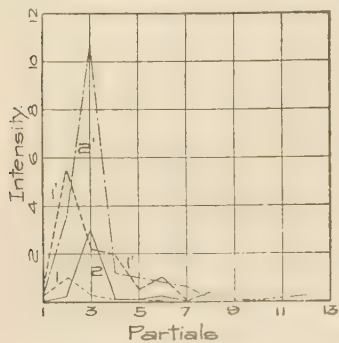


Fig. 8.

will be noted that while all the partials are increased in intensity by the stronger bowing, some higher ones are brought out which were not before present in measurable amount. Records (2) and (2') are similarly taken from a somewhat "scratchy" violin of not very powerful tone, age and make unknown. The same sort of effect from strong bowing is shown as in the first case. It is interesting to

note that among the differences introduced by different bowing, the individuality of each instrument still appears very clearly.

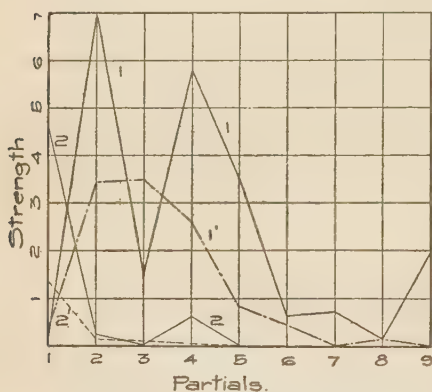


Fig. 9.

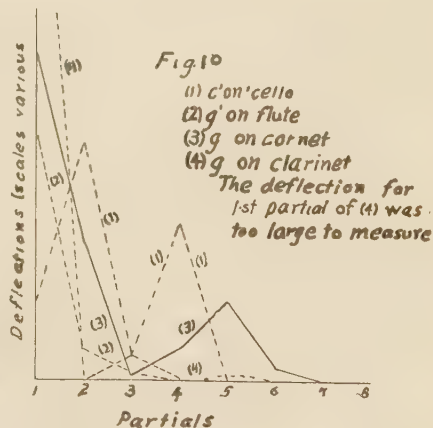


Fig. 10.

Fig. 9 shows the effect of varnishing. Through the kindness of Mr. Della Torre of this city a violin was obtained and strung "in the white," *i. e.*, without any varnishing at all. After making a record with it thus, he applied a varnish of his own and another record was taken.¹

The three modifications of tone just mentioned, *i. e.*, muting, difference of bowing, and varnishing, are the only ones yet sufficiently tested to be reported on. It is hoped that the test may be continued long enough to get valuable data as to the effects of various other factors which easily suggest themselves, such as setting of sound post, position, shape and height of bridge, graduation of back and belly, etc.

Fig. 10 shows records of several other instruments which need not be here discussed. Each one of these instruments, however, ought to be studied in the same complete way as has been suggested for the violin.

VII. VIOLIN TONE.

The question put before us is, what constitutes good violin tone? Some suggestions for an answer may be found in Fig. 11,

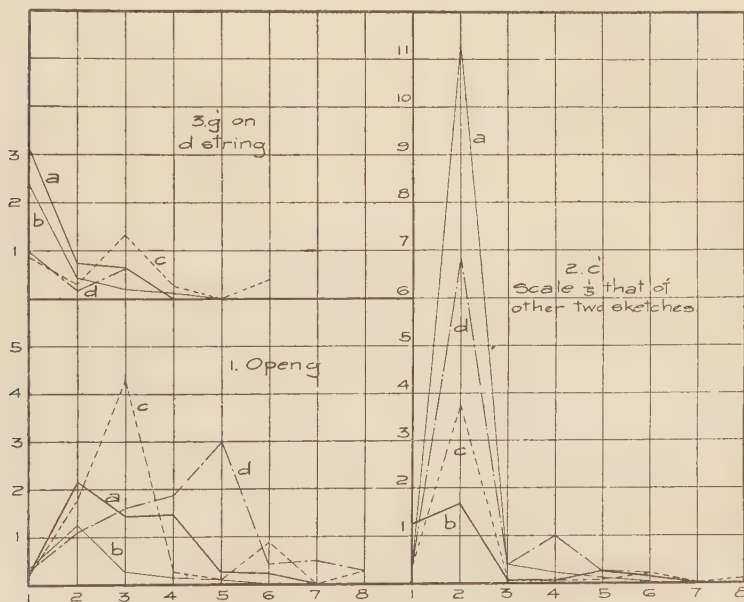


Fig. 11.

¹ It may be added that after varnishing this seemed to be an extremely good violin, as indeed will appear from the similarity of its curves to those of the best instrument shown in Fig. 11. It remains of course to see the effect of aging on its tone-quality. All the parts were adjusted and graduated with the greatest skill and care by Mr. Della Torre, who is a master in this line, and the result leads us to hope that good violins will not vanish from the world when the Cremonas wear out.

which shows the records of several instruments tested. So far as the writer can judge at present, the nearest approach to the ideal is represented in record (a), which is from a very valuable violin owned, and very kindly brought to the laboratory and played for me, by Professor Van Hulsteyn, of the Peabody Conservatory of Music. A rough attempt has been made to arrange the other records in order of decreasing merit of the instruments, but no great weight should be given to this order now. First a considerable number of the very best instruments should be very carefully compared in order to arrive at an idea of what ideal violin tone would be, and then it will be easier to classify various specimens by their deviations from this standard. It will be found, of course, that a great many violins will approach the standard in some parts of their range, while they will fall away from it in others.

VIII. THE VOWELS.

Our method ought to be useful in attacking the very interesting and unsettled question of the composition of the vowels. Figure

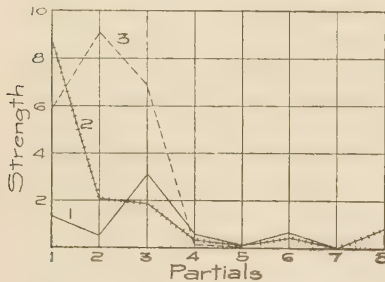


Fig. 12.

12 shows specimen records of a few vowels,¹ but the question is far too large to be discussed on the basis of the limited number of experiments we have so far been able to carry out in this line.

There seems no reason why some such device as this might not be used to test voices for training, first to find whether the voice has possibilities, and then to test the effects of a given method of training in bringing the voice up to what might be settled on, as indicated above for the violin, as a standard of quality for a voice of that range. Of course it is not meant that we must subject voices to an absolutely mechanical criterion, but a physical test ought to prove of great assistance.

¹Only a very few of a number of observations are here figured, as it seems useless to give a large number of undigested results.

SUMMARY.

1. The method devised gives *quantitative* records of the composition of sounds *actually emitted* from instruments, in terms of the energy of the partials.

2. The quality of a sound heard in a room with reflecting walls depends on the position of the instrument producing the tone, and of the hearer.

3. The lowest tones of a violin are almost lacking in fundamental.

4. Muting increases fundamental and decreases overtones in the lower tones of a violin; in the higher ones it decreases all the constituents.

5. In a good violin the lower tones are weak in fundamental and strong in the first two or three overtones, the energy rapidly disappearing towards the sixth or eighth partial. For higher tones fundamental increases and overtones die out, so that on the *a* string there is scarcely any overtone above the second partial. The seventh partial rarely appears in noticeable amount in any tone.

6. Some records were made of other instruments and of vowel qualities, but are not discussed.

My thanks are due to Professor Ames for his interest and help throughout the course of these experiments. Dr. Anderson has largely given direction to the work from the beginning, and many of the experimental details have been worked out by his assistance and that of Dr. Pfund. Dr. Watson, of the psychological laboratory, has given valuable help by putting at my disposal certain acoustical apparatus belonging to that laboratory. I cannot omit to put on record my appreciation of the helpful interest of many of the musical people of Baltimore, including several members of the staff of the Peabody Conservatory, and some musical dealers of the city.

PHYSICAL LABORATORY,
JOHNS HOPKINS UNIVERSITY.

LIFE.

Preston H. Edwards was born June 25, 1877, at Darlington, South Carolina. He attended private and public schools in Darlington, and studied at Furman University, Greenville, S. C., for two sessions, and three sessions at the University of Virginia, where, in June, 1900, he received simultaneously the degrees of B. A. and M. A. The subjects in which advanced work was taken for the Master's degree were Physics, Mathematics, Latin and Philosophy, and after this he took experimental courses in Physics and Chemistry during two summer terms at the University of Chicago. He taught two years in small schools in South Carolina, and served for two years as an Instructor in Physics at Miller Manual Labor School in Virginia, and for five years as Professor of Physics at Allahabad Christian College, Allahabad, India. Returning to America, he studied at Johns Hopkins University from February, 1908, to January, 1910, taking Physics, with Applied Electricity as First Subordinate and Mathematics as Second Subordinate. He attended lectures under Professors Ames, Wood, Whitehead and Cohen, and Doctors Anderson and Pfund, also under Professor Bloomfield.

During the session of 1908-09 he was Fellow in Physics, and during the rest of his stay was Fellow by Courtesy.

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